Gas Bubble Disease Monitoring and Research of Juvenile Salmonids

Annual Report of 1999 Research

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Executive Summary

This project began in 1995 with the primary objective of establishing a monitoring program to examine emigrating salmonids for signs of gas bubble trauma (GBT). We designed the GBT monitoring program and it is now part of the Smolt Monitoring Program. Project activities since 1995 have been to conduct research related to the GBT monitoring program.

We have conducted research to 1) assess the progression and severity of GBT signs in juvenile salmonids and relate signs to the likelihood of mortality, 2) investigate the rate of disappearance of signs of GBT, and 3) determine the *in-situ* migration depths and total dissolved gas (TDG) exposures of juvenile salmonids. The first two research topics have been completed; their results were summarized in an annual report (Maule et al. 1999) and three papers in peer-reviewed publications (Hans et al. 1999; Weiland et al. 1998; Mesa et al. 2000). This report summarizes data collected to determine the *in-situ* depths and TDG exposure of juvenile salmonids in an effort to determine if hydrostatic compensation offered some protection to juvenile salmonids migrating in water with high TDG. If this were true, it would explain differences between expected and observed signs of GBT found through the GBT monitoring program.

This research began in 1996 with an evaluation of a new pressure-sensitive radio tag for use in determining *in-situ* depths of juvenile salmonids (Beeman et al. 1998). The transmitter was subsequently used in field studies from 1997 through 1999 (Beeman et al. 1999a, 1999b). The objectives of this study were to: 1) investigate the feasibility of further reductions in tag size, 2) determine the *in-situ* migration depths of juvenile salmonids in McNary reservoir, and 3) determine *in-situ* depths of juvenile salmonids in the forebay of McNary Dam. The first objective was completed in 1997; it was determined that size of the current tag was largely determined by battery technology and could not be reduced without considerable cost (Beeman et al. 1999a). This report describes *in-situ* data collected in 1999. Findings to date include:

- The median migration depths of juvenile chinook salmon and steelhead in McNary reservoir were sufficient to compensate for ambient TDG levels from 117% to 126%, based on a 9.6% hydrostatic compensation per meter of depth. This corresponds to a compensation of 132 to 198 mm Hg of ambient total gas pressure. This level of compensation is enough to result in fewer signs of GBT than expected from shallow-tank bioassays. These results support finding fewer signs than expected in the GBT monitoring program, though this study did not attempt to quantify the expected prevalence or severity that could result from such a reduction in exposure.

- The exposures of juvenile salmonids to depth compensated TDG in McNary reservoir were lower in 1998 and 1999 than 1997 due to differences in TDG levels. The depths of juvenile chinook salmon increased slightly in 1998 and were almost one meter greater in 1999 than depths observed in 1997. Depths of juvenile steelhead were similar in each year. These results indicate that fish depth does not appear to be related to TDG levels.

- The median migration depth of juvenile chinook salmon in 1999 was 2.4 m, ranging from the

water surface to about 10 m. Steelhead had a slightly greater median migration depth of 2.7 m as well as a greater range of depths, from the water surface to about 12 m. The effective range of the equipment affected the maximum depths recorded, though most fish were located successfully. Fish depths in the near-dam forebay were shallower than in the nearby area of the reservoir.

- The migration rates through the study area in 1999 were intermediate of those observed in 1997 and 1998. Most fish migrations were direct, but some exhibited holding behavior similar to that observed after mid-May in 1997. Fewer fish displayed this behavior in 1999 and no relationship was found between holding behavior and date as noted in 1997. A comparison of results from 1997 and 1998 led to the hypothesis that river discharge and elevation were the most influential factors controlling migrations patterns. Results from 1999 indicate that other unmeasured factors may also influence the migration patterns of juvenile salmonids.

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Depth Histories of Individual Juvenile Salmonids in the Reservoir Between Ice Harbor and McNary Dams.

Introduction

The effects of fish depth on the susceptibility and recovery from gas bubble trauma (GBT) have been documented since the early 1900s (Gorham 1901; Dawley and Ebel 1975; Weitkamp 1976; Elston et al. 1997). These studies indicate that recovery can be accomplished with either time in equilibrated water or by increasing fish depth in supersaturated water. Knittle et al. (1980) found that 3 h at a depth of 3 m was sufficient for juvenile steelhead (*Oncorhynchus mykiss*) to fully recover from near-lethal surface exposures to 130% total dissolved gas (TDG) and resulted in additional protection from GBT when the fish were returned to the surface. A study by Aspen Applied Sciences, Inc. (1998) also found that chinook salmon (*O. tshawytscha*) exposed to similar conditions had a greater time to onset of mortality from GBT compared to fish held near the water surface, possibly due to reduction of bubble nucleation sites. Thus, information about the vertical histories (i.e., hydrostatic compensation) of individuals is important for a complete assessment of the effects supersaturated TDG may have on the prevalence or severity of GBT.

Several studies have examined the *in-situ* vertical distribution of individual juvenile salmonids in the Columbia River basin. These studies, however, have been based on hydroacoustic and gill net methods, which work at the population level and cannot be used to track the movements of known individuals (Monan et al. 1969; Smith 1974; Thorne et al. 1992; Feil and Rondorf 1998). The only study of the vertical distribution of individual salmon conducted in the Columbia or Snake rivers was an investigation of adult chinook salmon using pressure-sensitive radio transmitters (Gray and Haynes 1977). No work on individual juvenile salmonids had been conducted prior to this study, although the need for such research was recognized as early as 1980 (Weitkamp and Katz 1980).

The objective of this study was to determine the *in-situ* horizontal and vertical histories of individual juvenile salmonids in relation to TDG. We accomplished this by implanting miniature pressure-sensitive radio transmitters (tags) in fish and collecting data from individuals as they migrated between Ice Harbor and McNary dams.

Methods

Study Area

This study was conducted between Ice Harbor Dam on the Snake River, river kilometer (rkm) 15.6, and McNary Dam on the Columbia River (rkm 469.8). The study area was divided into four areas based on general differences in TDG, velocity, water depth, and influence of operating conditions at McNary Dam (Figure 1). The Snake area, defined as the reach from the

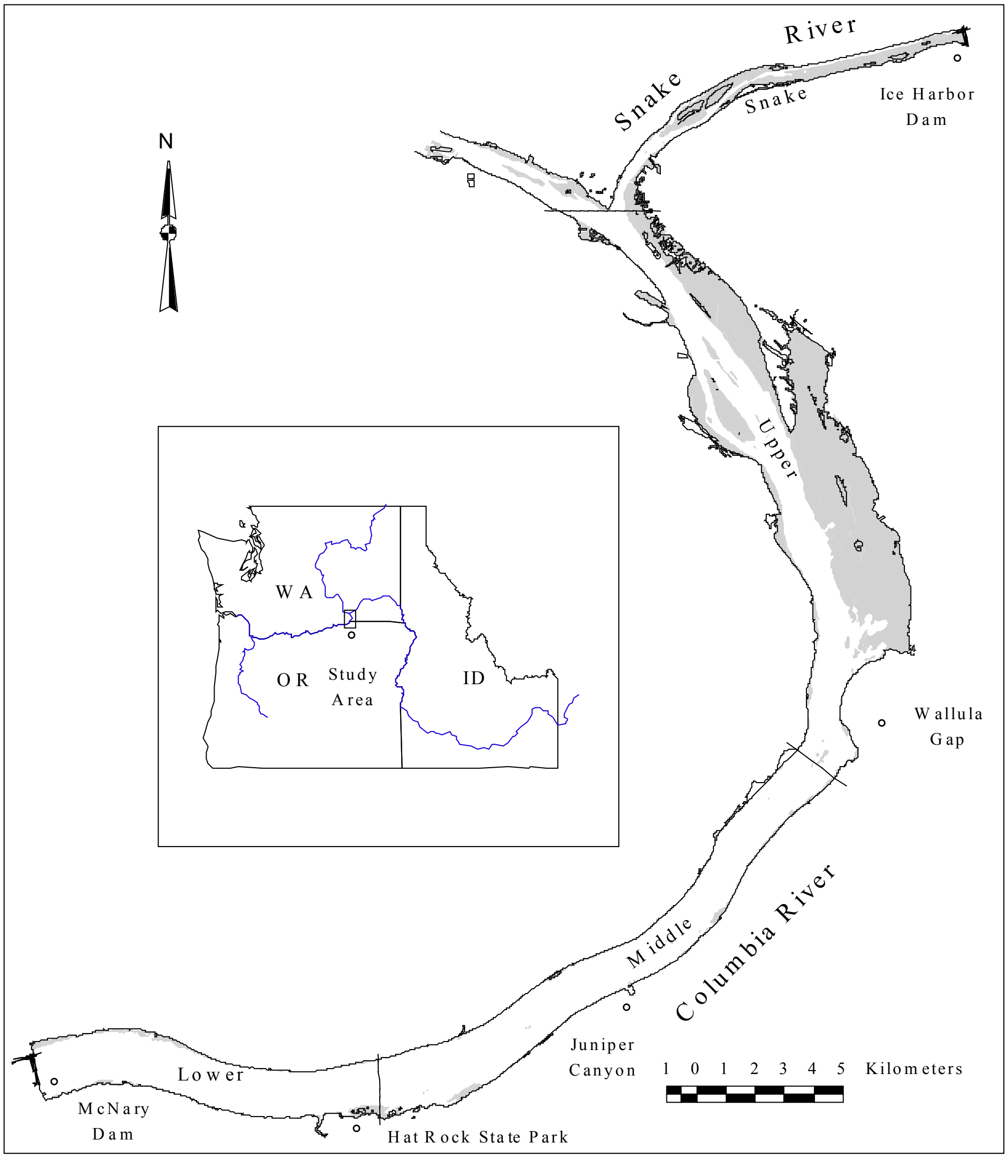

Figure 1. Map of the study area identifying major features as well as the four reservoir areas (Snake, Upper, Middle, Lower). Shaded area indicates water depth < 5.5 meters.

Ice Harbor Dam tailrace to the confluence of the Columbia and Snake rivers, is characterized by the highest TDG and highest water velocities of the four areas, as well as a large proportion of shallow water. The Upper area, from the confluence to the downstream end of Wallula Gap, is characterized by TDG components from the Columbia and Snake rivers and two regions with distinct water depths. The main river channel consists of depths of 10 to 14 m, whereas the area east of this region has lower water velocities and depths generally less than 3 m, with much of the area less than 1 m deep. The Middle area, from Wallula Gap to near Hat Rock State Park, typically contains water depths greater than 20 m. The Lower area, from Hat Rock State Park to McNary Dam, is similar to the Middle area, but the water velocities are more directly influenced by the operation of McNary Dam.

Fish Collection and Tagging

Yearling juvenile chinook salmon and yearling juvenile steelhead of hatchery origin were taken from the juvenile fish collection facility at Lower Monumental Dam on the Snake River (rkm 66.9) and transported to Ice Harbor Dam for tagging and release. Prior to transport, fish were anesthetized, identified in terms of species, age, and origin, and counted as part of the Smolt Monitoring Program. When possible, fish larger than 40 g were selected to reduce the probability of the implanted tag affecting fish behavior. The fish were placed in a 20-L bucket containing approximately 10 L of fresh water and carried to a 125-L insulated tank containing about 60 L of fresh water in a transport vehicle. The tank was insulated to minimize warming of the water during transport. Water in the transport tank was oxygenated at a rate of 0.5 L/min during transport to Ice Harbor Dam juvenile fish collection facility, a trip of approximately 45 min. A commercial aquarium water conditioner (Stress Coat, Aquarium Pharmaceuticals, Inc.) was added to the water at a concentration of 1:3785, as recommended by the manufacturer, to reduce fish electrolyte loss during transport. No more than four fish were taken from Lower Monumental Dam on any day.

Fish were surgically implanted with tags shortly after their arrival at the Ice Harbor Dam juvenile fish facility. The tags measured 23 mm x 7 mm and weighed 2.2 g in air (Beeman et al. 1998). Fish were anesthetized in solutions of 30 and 80 mg/L MS-222. Both anesthetic solutions included the water conditioner described earlier. Two fish were initially placed in a bucket containing 30 mg/L MS-222 for holding; they were then placed one at a time in a bucket containing 80 mg/L MS-222 shortly before surgery. After a fish lost equilibrium it was moved to a surgical table fitted with a gravity-fed system to irrigate its gills with 30 mg/L MS-222, fresh water, or any combination of the two via a small tube inserted into its mouth

A Plexiglas platform with a v-shaped recess was used to stabilize the fish body during surgery. Fish were placed ventral side up in the recess and the gills were continuously flushed with the anesthetic solution at a flow rate of approximately 250 ml/min. The anesthetic was replaced with fresh water to start the recovery process about one min before completion of the surgical procedure. The procedure took about 4 min per fish.

To implant a tag, a 10 mm-long incision was made 5 mm away from, and parallel to, the mid-ventral line starting about 5 mm anterior to the pelvic girdle. The incision was only deep enough to penetrate the peritoneum (Summerfelt and Smith 1990). A 50-mg/kg-body weight dose of oxytetracycline (100 mg/ml) was dispensed into the body cavity through the incision to prevent infection. A shielded-needle technique similar to that described by Ross and Kleiner (1982) was used to provide an outlet in the body wall for the antenna. An intravenous catheter was used to guide the antenna through the body wall of the fish. A catheter-covered needle was inserted through the incision to a point 5 to 10 mm posterior and slightly dorsal to the origin of the pelvic fins. Pulling the catheter back onto the needle exposed the point of the needle. Pressure was then applied until both the needle and catheter pierced the musculature and skin. The needle was then pulled back out of the incision, leaving the catheter in position to guide the antenna through the body wall of the fish.

The tag was implanted by threading the antenna through the end of the catheter at the incision; both the antenna and catheter were gently pulled posteriorly while the tag was inserted into the body cavity. The incision was closed with three simple, interrupted, absorbable sutures evenly spaced across the incision. The exposed antenna was attached to the side of the fish with a single suture placed 5-6 mm posterior to the exit site. The incisions and sutures were covered with a small amount of veterinary-grade cyanoacrylate glue to ensure the knots would not untie. Tagged fish were placed into a 20-L bucket containing oxygenated water and water conditioner for recovery after which they were sequestered in one of two 125-L insulated tanks (described earlier) for a minimum of 24 h prior to release. The tanks were supplied with fresh water passed through a 1-m packed column to remove supersaturated gas. No more than two fish were placed in each tank.

The fish were released from boats into the powerhouse and spillway sides of the Ice Harbor Dam tailrace after recovery from surgery. Each tank was dewatered until approximately 40 L of water remained, placed in a vehicle, and transported for approximately 10 min to the river's edge below the dam. Each tank was then lifted into a boat, after which the boats immediately moved to the release locations. The release sites were located approximately 1.0 to 1.5 km downstream from Ice Harbor Dam and approximately one-third the river width from each shoreline. These locations were chosen to provide a consistently safe release point over a wide range of river flows through Ice Harbor Dam. Fish were released at sunset by gently pouring the tank contents over the gunwale of each boat into the river.

Detecting tagged fish from boats

We attempted to locate each fish at one-hour intervals during their migration between the Ice Harbor Dam tailrace and McNary Dam forebay. Two 7-m inboard jet boats equipped with a Lotek SRX-400 telemetry receiver and 6-element Yagi antenna were used to locate tagged fish. A Common Sensing model TBO-L TDG meter was used to monitor the total gas pressure (TGP), water temperature, and barometric pressure (BAR) at each fish location. The reservoir depth was determined using a commercially available fish finder. Reservoir depths were corrected for the distance from the transducer to the water surface prior to analysis. The spatial locations of the tags were determined using a Trimble Pro-XR real-time, differentially corrected global positioning system (GPS) with spatial coordinates collected in NAD27, Washington South datum. Distances from landmarks, used as a redundant method of spatial location, were measured using a Raytheon R20-XX RADAR. Each boat was initially designated to collect data from half of the tag frequencies released. Data collection began immediately after release.

Several methods were used to locate tagged fish. The distance the boats searched from shore depended on the river depth and width. Previous research indicated the tags could be detected from distances of 356 m at a tag depth of 10 m to 1133 m at a depth of 2 m (Beeman et al. 1998). Tracking protocols were based on this information assuming all tags could be heard at a minimum effective scanning radius of 300 m from the boat-mounted antenna. This protocol was determined to be reasonable since the gain (i.e., sensitivity) of the receiving system under field conditions could often be increased over that used to determine tag reception distances by

Beeman et al. (1998). Land-based trackers, using a vehicle equipped with a receiver and 4-element Yagi antenna, assisted boat crews locating fish. They reported the passage of fish out of the Snake River and helped boats locate fish in the Middle and Lower areas by driving along the shore while scanning the proper frequencies. Land-based tracking proved most useful in the second capacity after periods of inclement weather reduced the mobility of boats. In these cases, the spatial locations of fish were determined by boat with the aid of the land-based crews.

The operator varied the gain of the receiving system to affect its range and directionality. The gain was set as high (typically 80 to 95 on a scale of 0 to 99) as background noise permitted while searching for tags and was reduced progressively after a tag was located to determine its position more accurately. A received signal strength approximately 6 dBm over the recording threshold was required to collect repeatable depth data from the tags (Beeman et al. 1998). Thus, data with received signal strength below this limit (received power of 100 on a scale of approximately 45 to 232) were ignored when recording depth data. The effective range of the receiving system was further reduced prior to recording the spatial location of the tag to enable a more accurate location estimate. The operator reduced the system gain until a received signal of -97 dBm (gain = 50) was required to be recorded by the receiver. Data was accepted from the tag when the received signal was 6 dBm over this threshold (i.e., power $\geq$ 100).

The pulse interval, relative strength of the radio signal, water depth and temperature, spatial location, BAR, and TGP were recorded on a data sheet and entered into a hand-held data logger each time a fish was located. The TGP and water temperature were measured with the TDG probe at the lesser of either the fish depth, as indicated by the tag, or a depth of 5 m. This produced measurements reflecting the environment at the fish depth. The probe was kept a minimum of 1 m from the river bottom for safety. Data sheets and electronic data were removed from the boats at the end of each 8-h shift. Data were proofed and analyzed using the SAS System for Personal Computers (SAS Institute, Inc. 1989).

Two methods were used to collect fish depths and locations. The primary method was to locate each fish and record location, depth, and other data at one-hour intervals in order to determine the exposure history of each fish. We also collected depth information from fish at one-min intervals over a 15-min period to determine the magnitude of vertical movements on a finer scale. In addition to fish depth, we recorded the water depth and temperature at the beginning of each 15-min period. This data was collected from fish located nearest dawn, noon, dusk, and midnight each day.

Total dissolved gas meters were calibrated at regular intervals. Field calibrations consisted of checking the silastic tubing for leaks, observing the indicated BAR, applying a pressure of 200 mm Hg, and adjusting the indicated TGP as necessary until TGP = BAR + 200 $\pm$ 2 mm Hg. Temperature was checked using a water bath and mercury thermometer. Instrument barometers were compared against each other to detect aberrant values after initial calibration using a mercury wall barometer.

Data analysis

The uncompensated total dissolved gas pressure as a percent of BAR (TGP_{uncomp}) was determined for each fish location based on TGP, BAR and fish depth. The TGP_{uncomp} is the actual TDG aquatic animals experience after accounting for the compensatory effects of hydrostatic pressure (i.e., the effective TDG). The TGP_{uncomp} is calculated using the equation:

$$TGP_{uncomp} = [TGP / (BAR + \rho g Z)] * 100\%$$

where ρ = density of water, kg/m^3, g = acceleration due to gravity, 9.80665 m/s^2, and Z = depth in m (Colt 1984). We assumed ρg was constant at 73.5 mm Hg. This assumption ignores changes in the density of water due to temperature and salinity. Variations in water density due to these factors were less than 0.1 mm Hg under our study conditions. The modified equation describes a hydrostatic compensation of 9.6 percentage points of saturation for each meter of depth. Alternatively, one may calculate ΔP_{uncomp} as $[(TGP\text{-}BAR) - \rho g Z]$, in units of mm Hg. The effect of hydrostatic compensation in these terms corresponds to a reduction in ΔP_{uncomp} of 73.5 mm Hg per meter of depth. The depth at which TGP_{uncomp} equals 100%, or ΔP_{uncomp} is zero, is the hydrostatic compensation depth.

Several corrections were applied to data from the tags. Differences between working and calibration temperatures were corrected using the method described in Beeman et al. (1998). Differences in atmospheric pressure at the calibration site (Isanti, Minnesota, elevation 288 m above mean sea level) and the study site (McNary full-pool elevation 103 m above mean sea level) were corrected by subtracting 0.2 m from all recorded depths. Corrected depths less than or equal to 0.0 m were assumed to be equal to 0.01 m. Data indicating negative depths are possible when fish are near the surface because the tag precision is ∀0.32 m (Beeman et al. 1998). This correction was required in 1.1% of the depths collected. Depths greater than approximately 12.5 m were omitted from the analysis because they are deeper than the range of the equipment. Depths greater than this maximum could occur due to data entry errors, low received power, or malfunctioning transmitters. These data comprised less than 0.2% of the depths collected.

Results

We released 30 juvenile spring chinook salmon over 12 dates between 12 April and 28 May and 42 juvenile steelhead over 14 dates between 12 April and 01 June (Table 1). The mean weight of chinook salmon was 61.8 g (range 39.2 to 125.5 g), yielding a mean tag-to-body- weight ratio of 3.6% (range 1.8 to 5.7%). The mean weight of steelhead was 101.2 g (range 60.1 to 166.4 g), resulting in a mean tag-to-body-weight ratio of 2.2% (range 1.4 to 3.7%).

Table 1. Tagging and release data for juvenile hatchery steelhead (STHD) and spring chinook salmon (HSPC) released from Ice Harbor Dam during spring, 1999. Radio tag frequency (frequency), species, tagging date, tagging start time (ST), tagging end time (ET), fork length (FL), body weight (Weight), release time, and release site (S = spillway side, P = powerhouse side). "nd" indicates no data available.

Frequency (MHz)	Species	Tagging Date	Tagging ST	Tagging ET	FL (mm)	Weight (g)	Release Time	Release Site
				Release Date 4/12/99				
150.256	HSPC	4/11/99	18:03	18:08	172	48.4	20:00	S
150.364	HSPC	4/11/99	18:11	18:16	161	43.8	20:00	S
150.402	STHD	4/11/99	18:28	18:33	222	98.4	20:00	P
150.586	STHD	4/11/99	18:36	18:40	230	107.6	20:00	P
				Release Date 4/14/99				
150.424	STHD	4/13/99	17:47	17:52	220	96.7	19:41	S
150.445	STHD	4/13/99	17:58	18:02	198	69.6	19:41	S
150.524	HSPC	4/13/99	17:26	17:30	167	46.6	19:41	P
150.565	STHD	4/13/99	17:34	17:38	221	107.1	19:41	P
				Release Date 4/17/99				
150.294	HSPC	4/16/99	18:16	18:20	176	54.6	19:59	S
150.323	STHD	4/16/99	18:22	18:27	267	159.3	19:59	S
150.483	STHD	4/16/99	nd	17:42	235	111.8	19:59	P
150.546	STHD	4/16/99	17:48	17:53	270	166.4	19:59	P
				Release Date 4/19/99				
150.272	HSPC	4/18/99	nd	nd	192	75.7	19:52	S
150.384	STHD	4/18/99	18:02	18:06	222	96.3	19:52	S
150.503	HSPC	4/18/99	18:14	18:18	170	55.2	19:52	P
150.604	STHD	4/18/99	nd	nd	234	142.8	19:52	P
				Release Date 4/26/99				
150.515	HSPC	4/25/99	17:24	17:27	183	59.9	20:09	S
150.654	HSPC	4/25/99	17:28	17:32	157	42.6	20:09	S
150.674	HSPC	4/25/99	nd	nd	194	72.8	20:09	P
150.695	HSPC	4/25/99	17:45	17:50	196	72.0	20:09	P

Release Date 4/28/99

150.215	HSPC	4/27/99	17:48	17:52	178	59.9	20:26	S
150.732	HSPC	4/27/99	17:53	17:57	167	44.3	20:26	S
150.794	HSPC	4/27/99	18:05	18:09	197	77.4	20:25	P
150.834	HSPC	4/27/99	18:12	18:16	159	44.8	20:25	P

Release Date 4/30/99

150.343	STHD	4/29/99	Nd	nd	240	109.7	20:12	S
150.462	STHD	4/29/99	Nd	nd	231	103.6	20:12	S
150.812	STHD	4/29/99	17:44	17:49	244	127.3	20:12	P
150.854	STHD	4/29/99	nd	17:55	217	95.1	20:12	P

Release Date 5/2/99

150.374	HSPC	5/1/99	17:52	17:56	235	125.5	20:19	S
150.434	HSPC	5/1/99	nd	18:01	167	46.9	20:19	S
150.573	HSPC	5/1/99	nd	18:08	179	65.6	20:19	P
150.593	STHD	5/1/99	18:09	18:13	227	101.2	20:19	P

Release Date 5/4/99

150.494	STHD	5/3/99	nd	nd	217	83.4	20:08	S
150.535	STHD	5/3/99	nd	nd	202	65.9	20:08	S
150.634	STHD	5/3/99	nd	nd	236	124.5	20:08	P
150.755	STHD	5/3/99	nd	nd	242	127.5	20:08	P

Release Date 5/10/99

150.354	STHD	5/9/99	17:20	17:23	204	72.8	20:39	S
150.415	STHD	5/9/99	17:26	17:30	202	72.7	20:39	S
150.713	STHD	5/9/99	17:34	17:40	235	120.4	20:39	P
151.894	HSPC	5/9/99	17:42	17:46	170	49.0	20:39	P

Release Date 5/12/99

150.314	HSPC	5/11/99	17:28	17:32	213	88.3	20:17	S
150.453	HSPC	5/11/99	17:34	17:39	216	94.7	20:17	S
150.774	HSPC	5/11/99	17:42	17:46	185	58.7	20:17	P
151.383	HSPC	5/11/99	17:47	17:52	190	68.7	20:17	P

Release Date 5/15/99

151.015	STHD	5/14/99	17:55	17:59	220	86.7	20:22	S
151.135	STHD	5/14/99	18:09	18:13	204	78.5	20:22	P
151.193	STHD	5/14/99	18:03	18:06	230	98.6	20:22	S
151.734	STHD	5/14/99	18:19	18:22	212	84.3	20:22	P

Release Date 5/17/99								
151.053	HSPC	5/16/99	18:05	18:09	170	48.3	20:24	S
151.085	HSPC	5/16/99	18:15	18:18	168	51.7	20:24	S
151.116	HSPC	5/16/99	18:22	18:26	226	118.4	20:24	P
151.123	HSPC	5/16/99	18:29	18:33	198	75.4	20:24	P
Release Date 5/24/99								
151.064	STHD	5/23/99	16:38	16:42	232	90.3	20:53	S
151.144	STHD	5/23/99	16:44	16:47	232	100.2	20:53	S
151.173	STHD	5/23/99	16:53	16:56	198	71.1	20:53	P
151.235	STHD	5/23/99	17:00	17:04	223	93.0	20:53	P
Release Date 5/26/99								
151.034	HSPC	5/25/99	16:51	16:55	173	44.6	20:38	S
151.074	STHD	5/25/99	16:58	17:02	226	103.1	20:38	S
151.094	STHD	5/25/99	nd	17:10	225	92.4	20:38	P
151.103	STHD	5/25/99	17:11	17:14	208	73.3	20:38	P
Release Date 5/28/99								
151.046	HSPC	5/27/99	nd	nd	168	39.4	20:37	S
151.152	HSPC	5/27/99	nd	nd	160	39.2	20:37	S
151.163	STHD	5/27/99	nd	17:35	246	125.8	20:37	P
151.252	HSPC	5/27/99	nd	17:39	162	42.7	20:37	P
Release Date 5/30/99								
151.183	STHD	5/29/99	nd	nd	214	88.1	20:39	S
151.293	STHD	5/29/99	nd	nd	212	94.1	20:39	S
151.354	STHD	5/29/99	nd	16:56	238	109.9	20:39	P
151.453	STHD	5/29/99	16:58	17:01	253	137.5	20:39	P
Release Date 6/1/99								
150.234	STHD	5/31/99	nd	16:58	208	78.0	20:40	S
151.333	STHD	5/31/99	17:00	17:03	234	108.1	20:40	S
151.411	STHD	5/31/99	17:07	17:11	195	60.1	20:40	P
151.433	STHD	5/31/99	17:15	17:18	230	118.4	20:40	P

During their migration from Ice Harbor Dam to McNary Dam, we located juvenile chinook salmon 632 times with a median of 20 times per fish (range 3 to 50). Juvenile steelhead were located 755 times with a median of 18 times per fish (range 2 to 47). The median depths of tagged juvenile chinook salmon and steelhead were 2.7 m (range 0.0 to 12.6 m) and 2.4 m (range 0.0 to 10.4 m), respectively. The median TDG measured at the location of each chinook salmon was 114.0% (range 102.2 to 130.7%) and 114.3% (range 102.3 to 130.4%) at steelhead locations, thus both species had a median compensation depth of 1.5 m (range 0.2 to 3.2 m).

The depth of fish was not static as they migrated through the reservoir, as both chinook salmon and steelhead frequently moved above and below the compensation depth. The median range of vertical movement of individual chinook salmon was 6.1 m (range 0.8 to 11.2 m). Steelhead had a median range of vertical movement of 5.6 m (range 0.1 to 9.7 m). Chinook salmon were located above the compensation depth 28% of the time while steelhead were found there 31% of the time, resulting in median TGP_{uncomp} levels of 88.7% and 90.7%, respectively.

We observed several trends as fish migrated through each of the four areas in McNary Reservoir; most reflected the flow regimes of the Snake and Columbia rivers. In the Snake area, fish tended to stay on the side of the river from which they were released for approximately 2 to 5 km, after which most traveled south of Strawberry Island in the navigation channel (Figure 2).

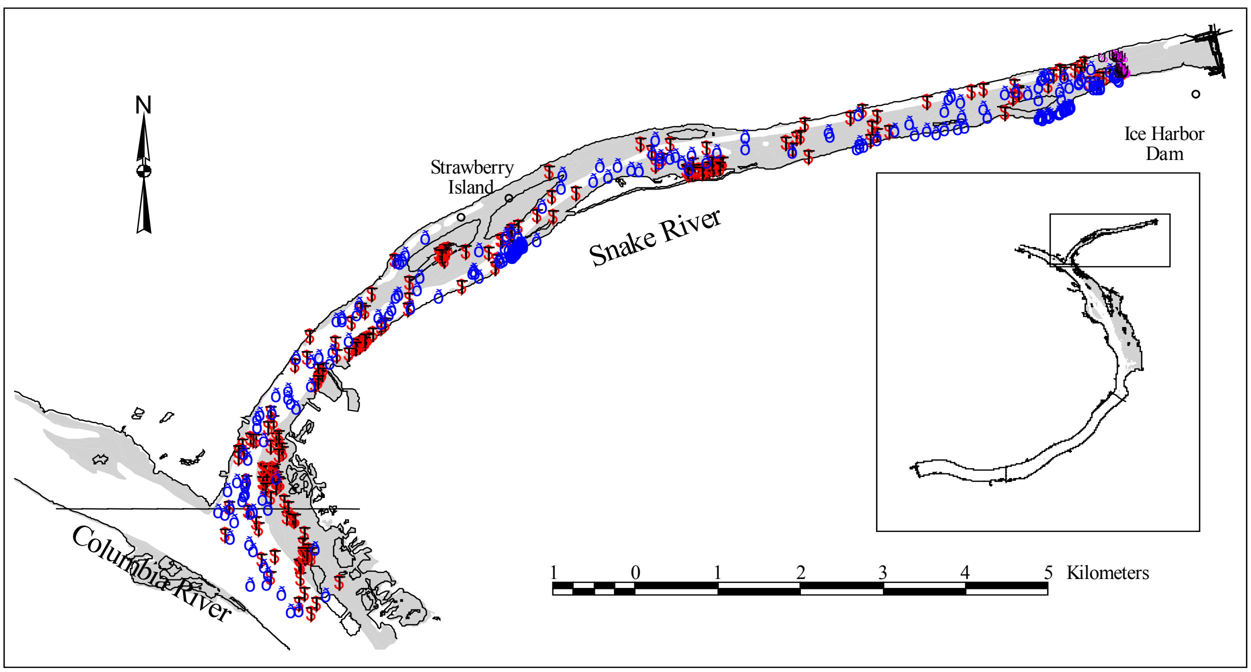

Figure 2. Spatial locations of radio-tagged juvenile spring chinook salmon (▲) and steelhead (ð) tracked in the Snake area during spring, 1999. Release locations (■) were approximately 1 km downstream from Ice Harbor Dam. Data collected from the area indicated by the box in the inset map are shown. Shaded area indicates water depth < 5.5 meters.

Fish moved out of the Snake River into the Upper area predominantly along the southeast shore. Most fish migrated through the Upper area nearest the east side and middle of the thalweg. Deviations from this pattern included a few fish located on the west shore as well as several individuals moving into shallow areas to the east (Figure 3). Thirteen fish were located in these

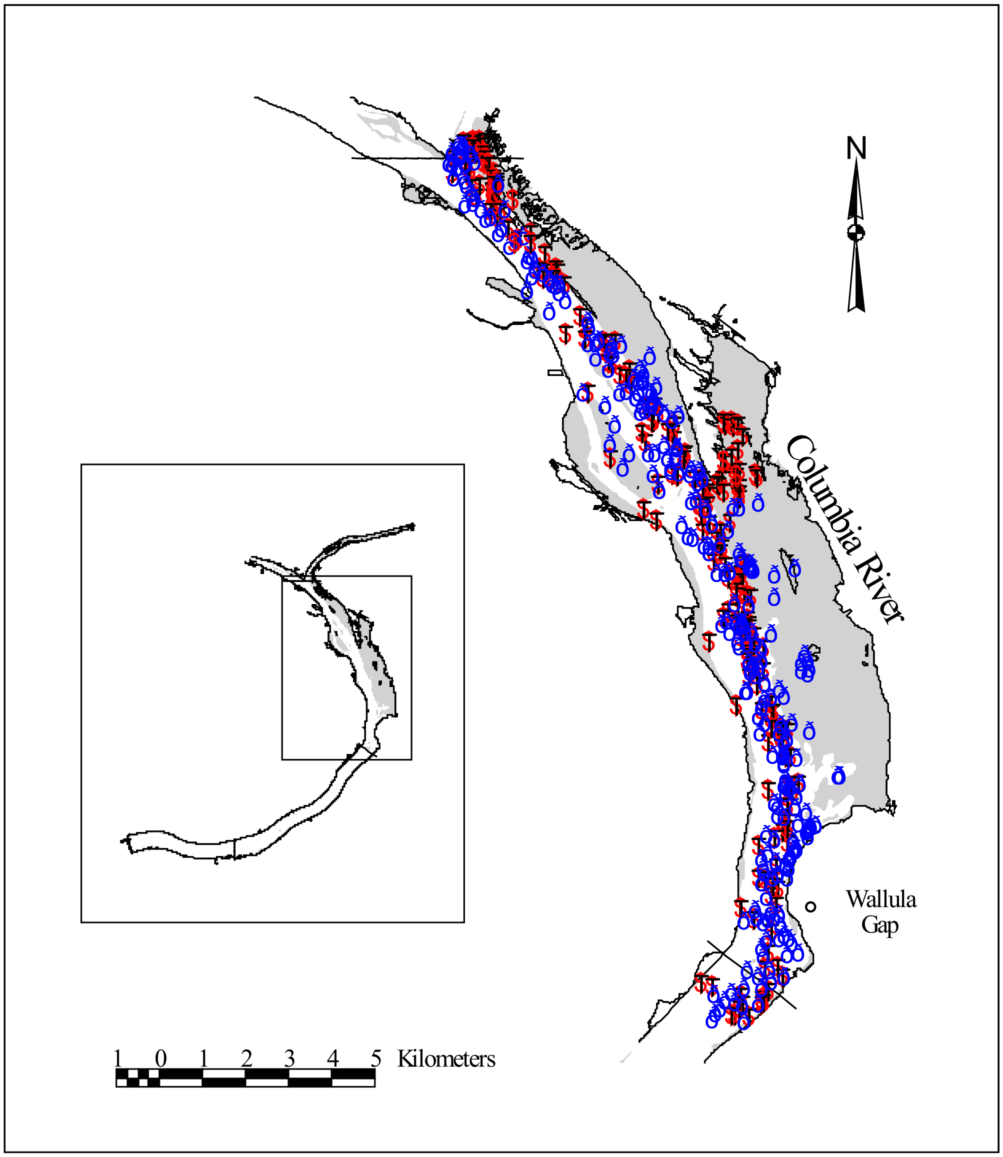

Figure 3. Spatial locations of radio-tagged juvenile spring chinook salmon (▲) and steelhead (ð) tracked in the Upper area during spring, 1999. Data collected from the area indicated by the box in the inset map are shown. Shaded area indicates water depth < 5.5 meters.

areas—three spring chinook and 10 steelhead. Most fish remained in the shallows only briefly; one chinook salmon and five steelhead remained there for 2 h or less. Only two fish stayed in this area for longer than 12 h—one steelhead for 18 h and one chinook salmon for 26 h. Few trends were observed in the Middle and Lower areas. Most fish traveled along the southeast side of the river for a few kilometers downstream of Wallula Gap, but showed no pattern through the remainder of the Middle area (Figure 4). Fish passing through the Lower area continued along the path on which they had left the Middle area. Their approach to McNary Dam appeared to be influenced by dam operations; fish usually moved toward the spillway and powerhouse sections of the dam in the middle of the reservoir (Figure 5).

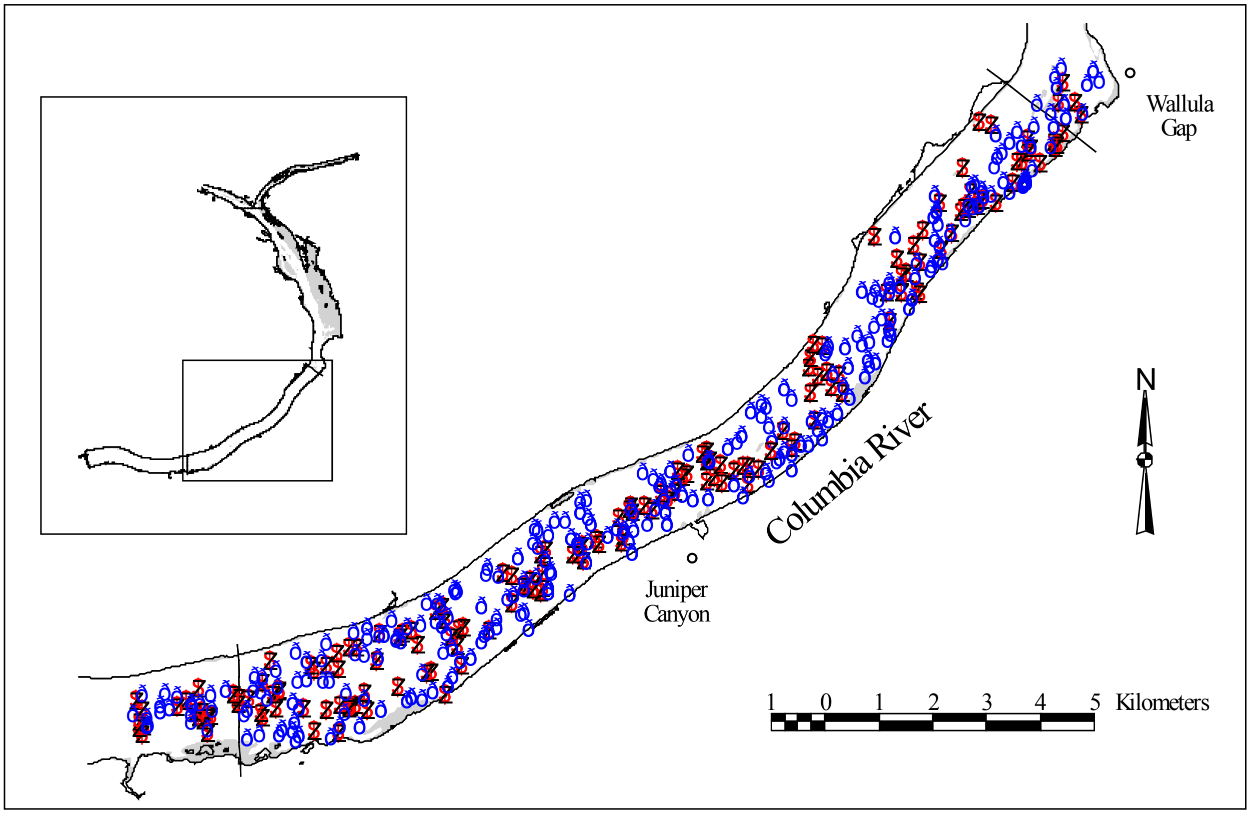

Figure 4. Spatial locations of radio-tagged juvenile spring chinook salmon (▲) and steelhead (♁) tracked in the Middle area during spring, 1999. Data collected from the area indicated by the box in the inset map are shown. Shaded area indicates water depth < 5.5 meters.

Median depths of chinook salmon were greater in the Middle and Lower areas than in the Snake and Upper areas (Figure 6A). Consequently, the median TGP_{uncomp} experienced by chinook salmon was less in the Middle and Lower areas than in the Snake and Upper areas (Figure 7A). Median depths of steelhead varied little between areas, ranging from 2.0 m in the Snake area to 2.7 m in the Middle area (Figure 6B). Median TGP_{uncomp} also varied little, decreasing slightly with downriver migration, ranging from 96.0% in the Snake area to 86.8% in the Middle area (Figure 7B). Median water depths at chinook salmon and steelhead locations increased similarly during their downriver migration (Figure 6). Median TDG at fish locations were very similar between species by reservoir area. Both species decreased somewhat with downstream migration (Figure 8), resulting in a median compensation depth that became shallower as fish moved through the study reach. The percent chinook salmon and steelhead locations above the compensation depth were highest in the Snake area and decreased as fish migrated downriver through the Upper and Middle areas. As fish moved into the Lower area the percent of locations of both species above the compensation depth increased slightly (Figure 8).

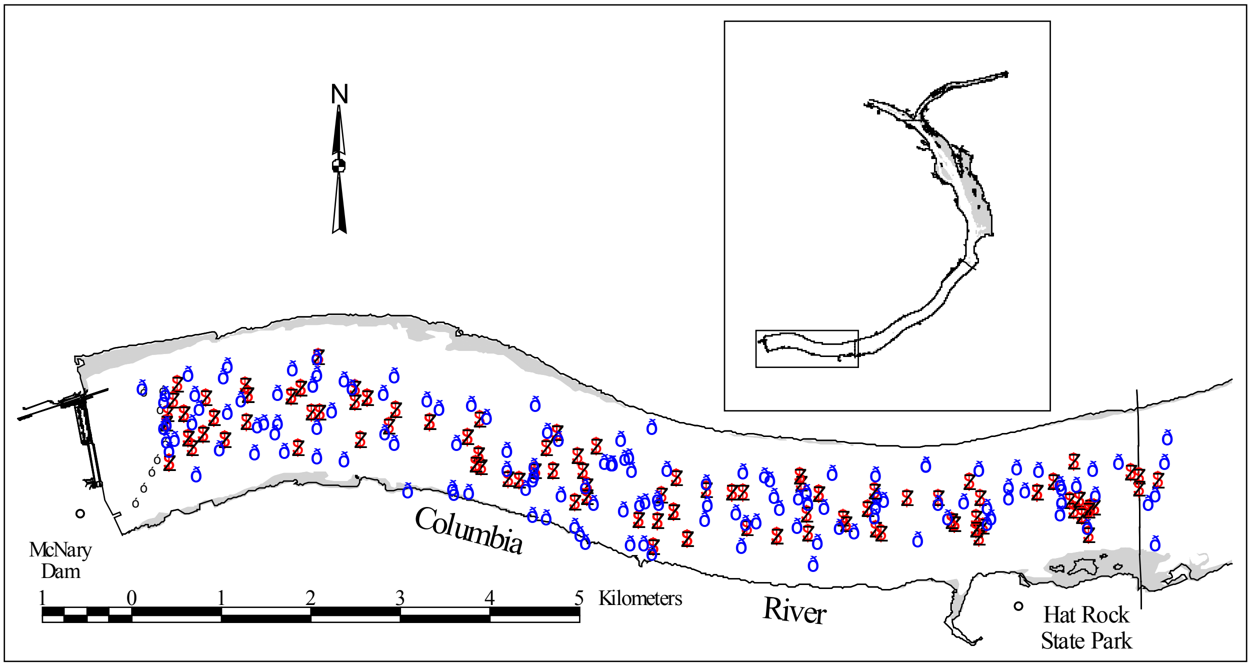

Figure 5. Spatial locations of radio-tagged juvenile spring chinook salmon (▲) and steelhead (ŏ) tracked in the Lower area during spring, 1999. Data collected from the area indicated by the box in the inset map are shown. Buoys marking the McNary Dam forebay boat restricted zone are indicated by ȍ. Shaded area indicates water depth < 5.5 meters.

Median travel times of chinook salmon (50.3 h, range 18.7 to 167.6 h) through the study area were slightly longer than those of steelhead (47.9 h, range 21.7 to 241.0 h). Median transit times of both species through each of the four areas of the reservoir were similar; the largest difference was in the Middle area where the median transit time of chinook salmon was 2.8 h longer than that of steelhead (Figure 9). Both species were exposed to the highest median TGP_{uncomp} levels and had the greatest percent of locations above the compensation depth in the Snake area, but they spent the least amount of time in this area (Figures 7 and 9). Conversely, the median transit times were about twice as long in the Upper area and about three times as long in the Middle and Lower areas than the Snake area, but the median TGP_{uncomp} and percent of locations above the compensation depth declined in the Upper area, and were lowest in the Middle and Lower areas. Median TDG levels at chinook salmon and steelhead locations followed similar patterns; TDG levels were highest in the Snake and Upper areas and lowest in the Middle and Lower areas (Figure 8).

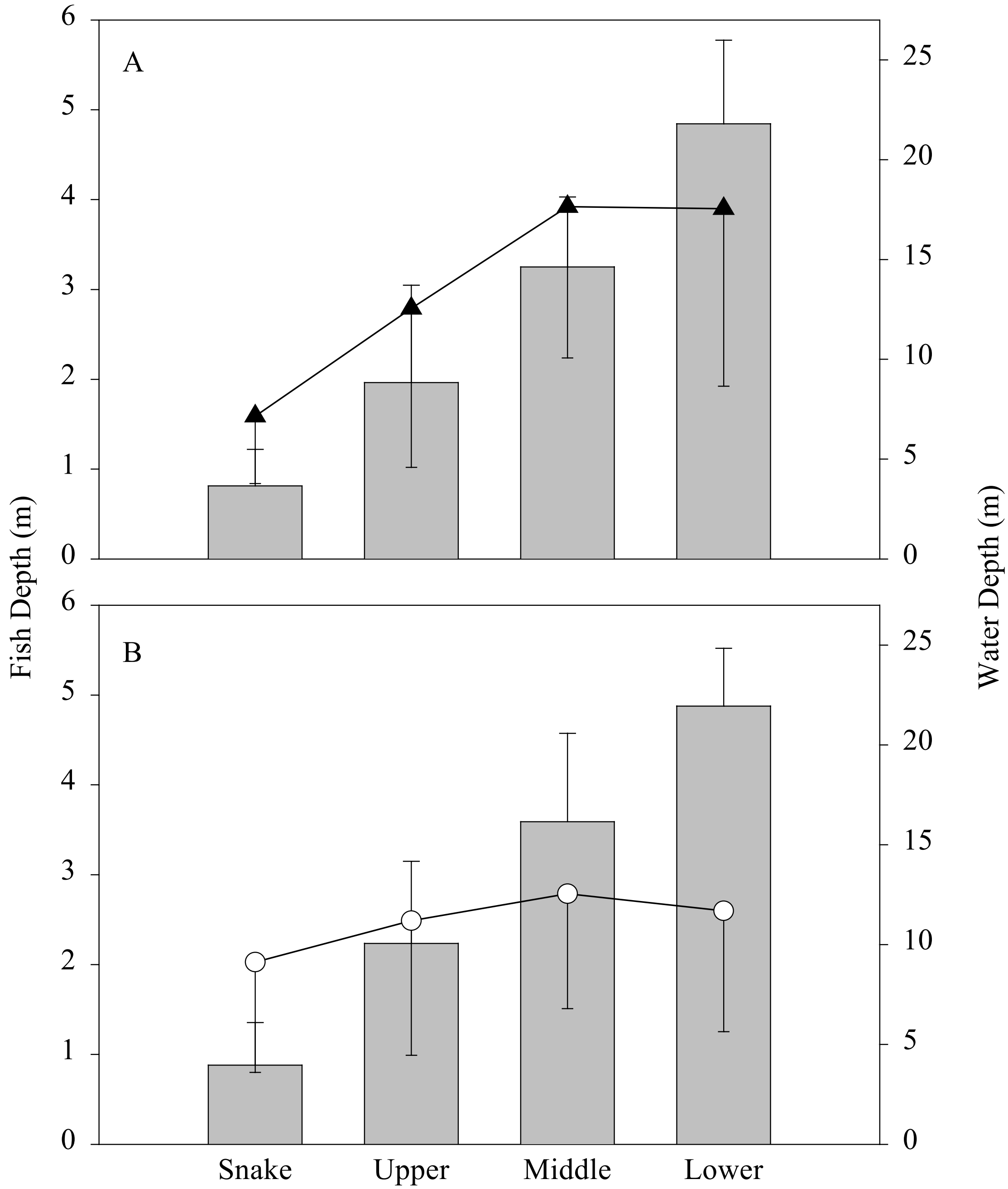

Figure 6. Median fish depth (lines) and median water depths (bars) of juvenile chinook salmon (A) and steelhead (B) by reservoir area during spring, 1999. Vertical lines indicate one-half inter-quartile range.

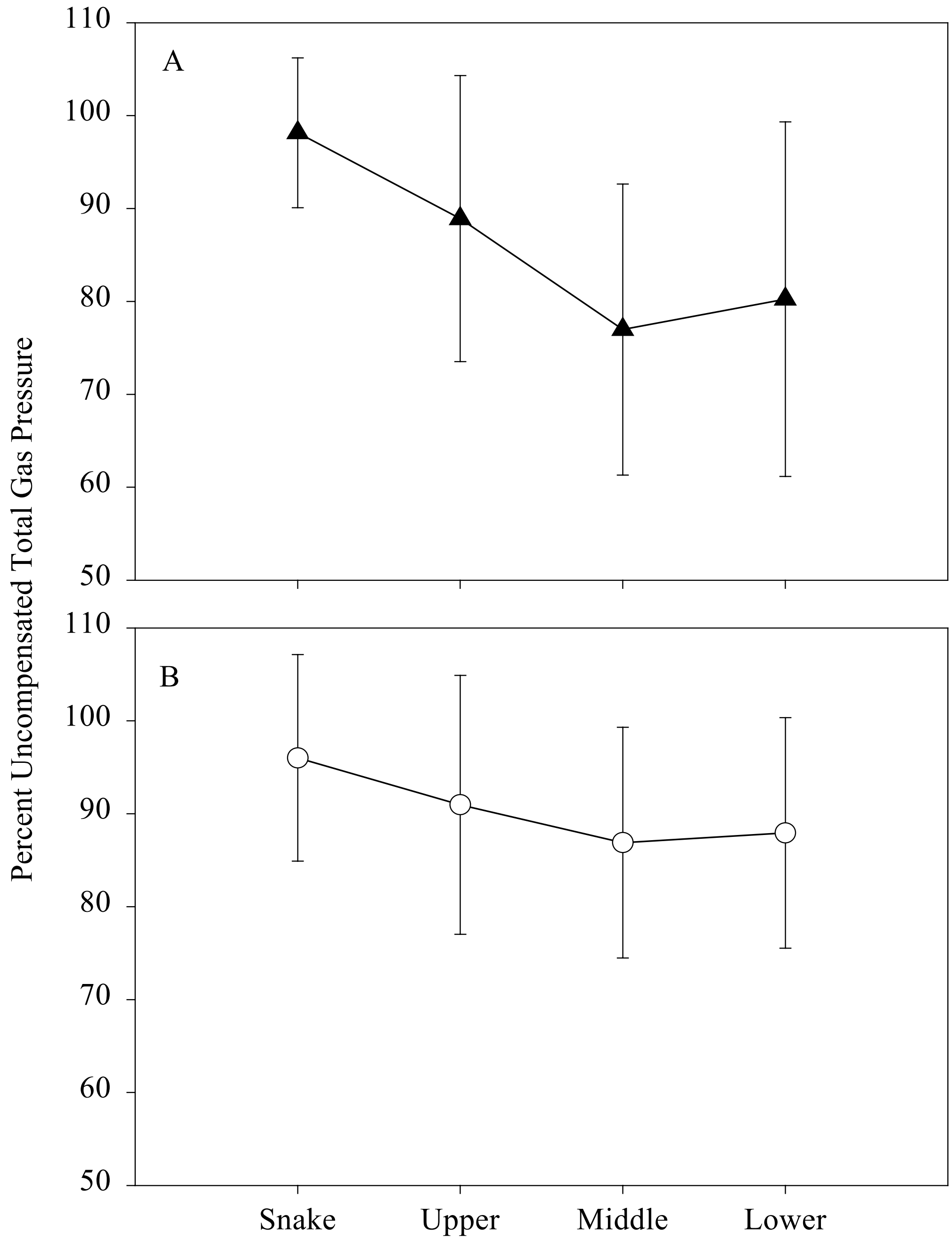

Figure 7. Median uncompensated total gas pressure of radio-tagged juvenile chinook salmon (A) and steelhead (B) by reservoir area during spring, 1999. Vertical lines indicate ± one-half inter-quartile range.

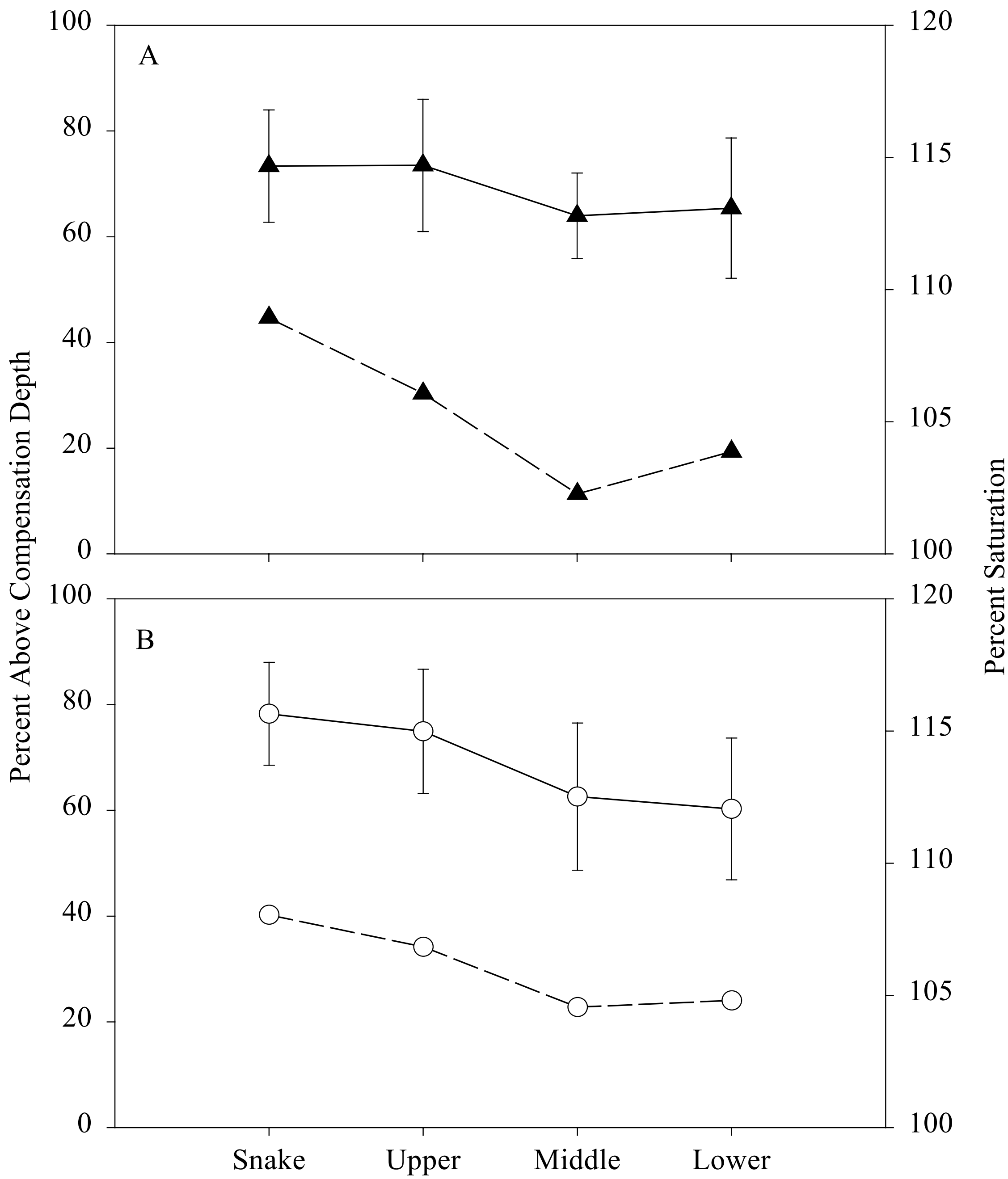

Figure 8. Percent of fish above the compensation depth (dashed lines) and median percent total dissolved gas saturation at locations (solid lines) of juvenile chinook salmon (A) and steelhead (B) by reservoir area during spring, 1999. Vertical lines indicate ± one-half inter-quartile range.

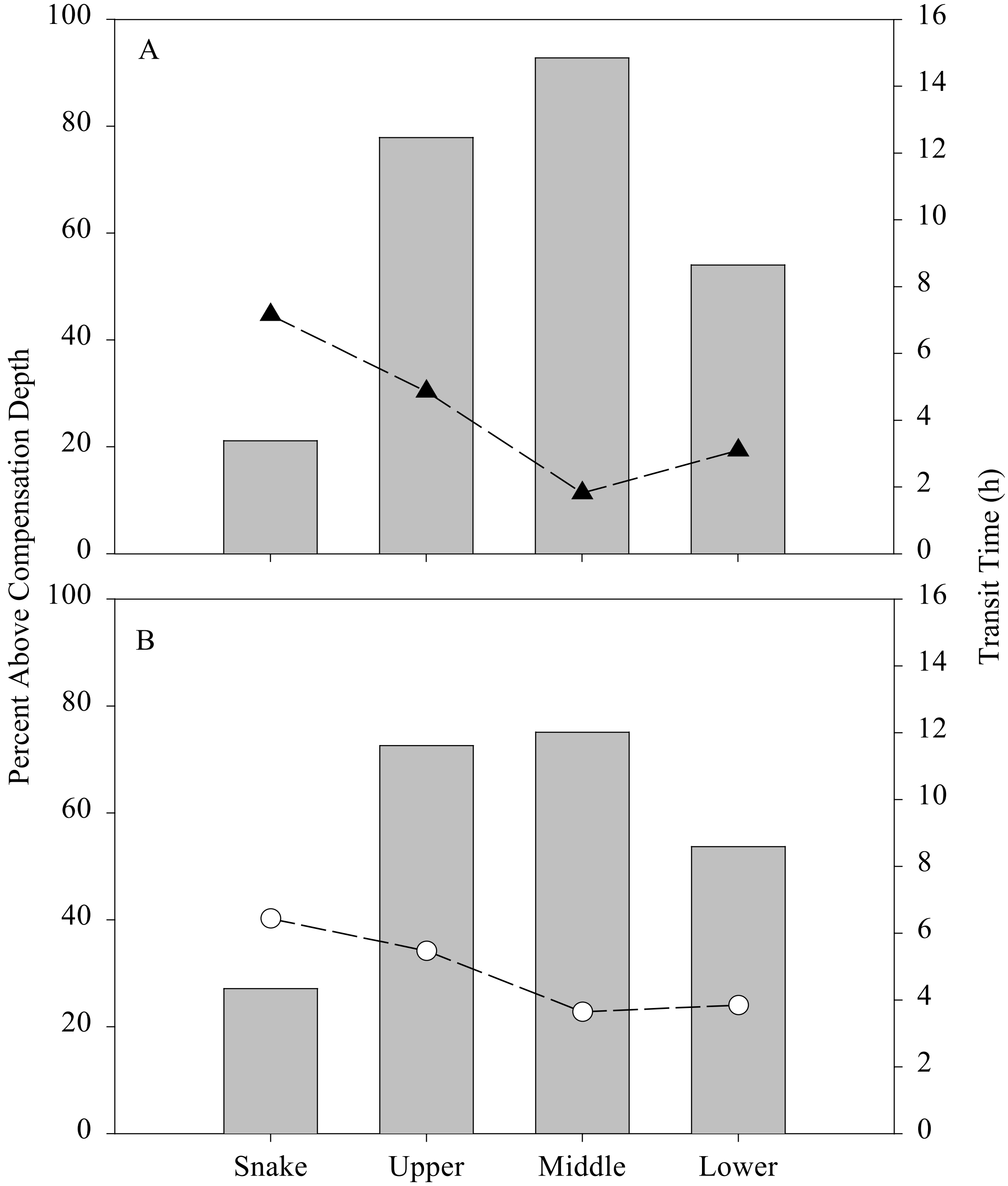

Figure 9. Percent of fish above the compensation depth (dashed lines) and median transit times (bars) of juvenile chinook salmon (A) and steelhead (B) by reservoir area during spring, 1999.

Data collected at one-minute intervals indicated that both chinook salmon and steelhead changed depths often and with considerable magnitude at times. We recorded 991 depths from 23 chinook salmon (range 12 to 112 depths per fish) and 1231 depths from 34 steelhead (range 13 to 76 depths per fish) at one-minute intervals. The median depths of both chinook salmon and steelhead from these data were 2.5 m and ranged from the surface (0 m) to maximum depths of 10.9 m and 12.1 m, respectively. Both species changed depth at a median vertical rate of 0.2 m/min; rates of depth change of chinook salmon ranged from 0.0 to 5.6 m/min and those of steelhead ranged from 0.0 to 9.2 m/min in steelhead.

Discussion

The results of this study indicate that the migration depths of juvenile spring chinook salmon and steelhead in the lower Snake and mid-Columbia rivers were sufficient to compensate for ambient TDG levels from 123 to 126%, based on a 9.6% hydrostatic compensation per meter of depth. This corresponds to a compensation of 176 to 198 mm Hg of ambient TGP. The 1999 data are similar to results from 1997 and 1998, during which innate vertical behaviors of these species compensated for TDG levels of 117 to 124% (132 to 184 mm Hg of ambient TGP; Beeman et al. 1999a, 1999b). These results suggest that the current voluntary spill program limit of 120% TDG in tailraces and 115% TDG in forebays is adequate to prevent the onset of GBT in most juvenile spring chinook salmon and steelhead given the innate vertical behaviors of these species.

We consider our estimates of reductions in exposure due to fish depth to be conservative because they do not account for all effects of hydrostatic pressure. Our estimates only account for the effects of pressure based on Henry's Law, which states that an increase in the solubility of a gas in solution is proportional to the pressure acting on the solution (Mortimer 1983). Applying this law to fresh water results in a 9.6% increase in the solubility of gasses per meter of depth, hence the 9.6% hydrostatic compensation allotted per meter of a fish's depth (Colt 1984). Reducing exposure durations to high TDG levels via the mechanism of hydrostatic compensation may cause fewer signs of GBT in migrating fish than would result from shallow-water bioassays. We suggest that hydrostatic compensation may account for the discrepancies found by the GBT monitoring program between observed and expected levels of GBT in migrating juvenile salmonids (Maule et al. 1997).

The risk of chinook salmon and steelhead developing GBT varied by area in 1999. Median depths of chinook salmon increased from 1.6 m in the Snake area to nearly 4 m in the Middle and Lower areas while steelhead depths only increased from 2 m in the Snake area to a maximum of 2.8 m in the Middle area (Figure 6). The pattern of median depths by reservoir area we observed was similar to that seen in 1997 and 1998; depths increased as fish moved downstream and chinook salmon depths changed to a greater degree than steelhead (Beeman et al. 1999a, 1999b). The only exception to this was steelhead in 1998; median depths of these fish were slightly deeper in the Snake and Upper areas than in the two downstream areas. As would be expected given the changes observed in median depth by area in 1999, the percent of locations above the compensation depth was higher for both species in the Snake and Upper areas and lowest in the Middle or Lower area (Figure 8). We also found that the levels of TDG were highest in the Snake and Upper areas (Figure 9). These factors combined to present the greatest risk to fish for developing GBT symptoms in the Snake and Upper areas. This risk was somewhat mollified by the fact that despite having conditions most conducive to GBT, the Snake area also had the shortest mean transit time of any area (Figure 9).

The overall risk of fish developing GBT was lower in 1999 than in past years of this study. One indication of this was that the percent of locations above the compensation depth was slightly below 1998 levels and much lower than in 1997, especially for chinook salmon. For steelhead, the difference between years is most likely due to lower TDG levels rather than a change in fish behavior. The median depth of 2.4 m in 1999 was virtually identical to observations from 1997 and 1998 while median TDG levels were about 6% lower in 1998 and 1999 than in 1997, thus the compensation depth was about half of a meter shallower (Beeman et al. 1999a, 1999b). The lack of a change in median depths combined with a shallower compensation depth suggests the decrease in steelhead located above the compensation depth we observed was due to lower TDG levels. The percent of chinook salmon locations above the compensation depth dropped from 61 to 28% from 1997 to 1999. It is unlikely that such a large change could be attributed to a single factor. In addition to the lower TDG levels observed in 1999, we found that chinook salmon had a median depth of 2.7 m. This depth is slightly greater than 1998 levels, but almost a meter deeper than the median depth in 1997 (Beeman et al. 1999a, 1999b). Changes in migration behavior may have also contributed to such a dramatic shift in chinook salmon located above the compensation depth. Delays in migration were observed in the second half of May during the 1997 migration when many fish entered the shallows east of the thalweg in the Upper area and remained there for several days prior to resuming their downstream migration. This change in migration behavior was accompanied by a change in median depths, which were almost half a meter shallower than those in the first half of May (Beeman et al. 1999a). We suggest that the decline in chinook salmon located above the compensation depth may be due to a number of factors including lower TDG levels, greater median depths, and differences in migration patterns.

The innate abilities of juvenile chinook salmon and steelhead to make large changes in depth over a short period of time may dramatically affect their susceptibility to GBT. As in past years, we found fish could change depth very quickly; maximum rates of vertical movement were 5.6 m/min for chinook salmon and 9.2 m/min for steelhead. The median rate of vertical movement of both chinook salmon and steelhead (0.2 m/min) was below the detection limit of the telemetry system (Beeman et al. 1998). This rate of change is similar to that seen in 1997 and 1998 when rates for both species ranged from 0.2 m/min to 0.3 m/min (Beeman et al. 1999a, 1999b). Changes in depth of the magnitude we observed could dramatically alter the TGP_{uncomp} a fish experiences and consequently its risk of developing GBT via the mechanism of hydrostatic compensation. There is also evidence of fish having increased resistance to GBT after time spent at depth (Knittle et al. 1980; Aspen Applied Sciences 1998). The hypothesized mechanism of this phenomenon is resorption or reduction in size of nucleation sites.

Migration patterns in 1999 were intermediate of those observed in 1997 and 1998; most migrations were direct, but some holding behavior was observed. We observed migration delays in the eastern shallows of the Upper area similar to those seen in late May 1997, but to a lesser degree (Figure 3). Fewer fish moved into these shallow areas and of those that did, most remained there only briefly. Another difference from delays observed in 1997 was the lack of any shift in behavior associated with a specific date. Fish moved into these shallow areas from mid-April through the end of May, a period encompassing the majority of our study. Beeman et al. (1999b) hypothesized that differences in migration behaviors observed between 1997 and 1998 were due to different flow regimes. The higher flows observed in 1997 increased water surface elevation, and it was suggested the elevation change might have altered current patterns at the interface of the navigation channel and shallows along the eastern edge of the Upper area directing migrating fish into the shallows. Data from 1999 does not necessarily refute the hypothesis of Beeman et al. (1999b), but may require the addition of a caveat. Flows in 1999 were more similar to those in 1998 than 1997 (data from U.S. Army Corps of Engineers), however, holding behavior was observed throughout the migration. While river flow most likely has the greatest influence on migration patterns, we suggest that fish behavior or other unmeasured factors may also have a perceptible effect.

In this study we found that the vertical behaviors of juvenile spring chinook salmon and steelhead were similar in 1997, 1998, and 1999. Median depths ranged from 1.8 to 2.7 m, which can be expected to compensate via hydrostatic pressure for a range of TDG levels from 117 to 126% (132 to 198 mm Hg of ambient TGP). These results suggest that the current voluntary spill program limit of 120% TDG in tailraces and 115% TDG in forebays is adequate to prevent the onset of GBT in these species. Median depths were sufficient to prevent GBT in most fish despite year-to-year differences in flow, spill, total dissolved gas, and migration behavior. We also found that fish depths increased and TDG decreased with distance from the Ice Harbor Dam tailrace, indicating that the risk of GBT was reduced with distance from the dam. This suggests that the physical river environment (e.g. river depth, currents, water velocity) may influence the vertical behavior of juvenile salmonids during their migration. Thus, instead of a static migration depth the vertical behavior of juvenile spring chinook salmon and steelhead would vary in response to the unique physical conditions of each river reach through which the fish migrate. We also found migration patterns through the Upper area differed in 1998 and 1999 despite similar river conditions. This indicates that in addition to the physical river environment, other unmeasured factors may influence migration behavior in juvenile salmonids.

Depth Histories of Individual Juvenile Salmonids in the Near-Dam Forebay of McNary Dam.

Introduction

Monitoring movements of radio-tagged fish near hydroelectric facilities is common in the Columbia River basin. Radio telemetry is currently being used to evaluate fish passage at several dams on the Columbia and Snake rivers. The typical goals of such research are to determine routes and rates of passage at specific locations.

Our use of radio telemetry to monitor tagged fish near McNary Dam had three objectives. The primary objective was to determine the depths of fish inside the boat-restricted zone (BRZ) of the McNary Dam forebay, as our mobile tracking ceased at the BRZ line. Our second objective was to use the equipment as an exit site to confirm tagged fish had left the study area. The final objective was to determine the route of dam passage. Route of passage was important to the U. S. Army Corps of Engineers for possible inclusion in their fish distribution model currently under development by the Walla Walla district. The configuration of the telemetry equipment at McNary Dam was based on these objectives.

Methods

Description of telemetry equipment

The near-dam forebay of McNary Dam was monitored for tagged fish using telemetry equipment mounted on the dam. This equipment consisted of three Lotek SRX-400A receivers with W-21A firmware, each monitored inputs from one to nine 4-element Yagi antennas. Antenna locations and designations are described in Figure 10.

The distances between antennas were based on the distance between turbine units, spillbays, and coverage of similar systems at other dams (Rip Shively, US Geological Survey, personal communication). Antennas were mounted on the powerhouse (P bank), spillway (S bank) and near the forebay lock entrance (L bank). Antennas of P bank were placed on the powerhouse piernoses between turbine units 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, 11 and 12, and 13 and 14; a distance of about 52 m apart. An additional antenna (P0) was added to the array in 1998 to increase coverage south of turbine unit one; it was mounted about 52 m south of P1. Antennas at S bank were placed approximately 55 m apart across the spillway. The locations were in front of spill bay 1 and between spill bays 3 and 4, 6 and 7, 9 and 10, 12 and 13, 15 and 16, 18 and 19 and 21 and 22. The input from S7 was combined with an antenna mounted on the adult fish ladder (S7a) in 1998 to increase coverage of the area between the adult ladder and spill bay 22. The antennas of P and S banks were positioned facing south at approximately 45 degrees from the dam face and down at about 15 degrees to maximize the area of coverage near the face of the dam and to reduce radio interference from dam operation. One antenna was used at L bank to monitor the area near the upstream lock entrance. It was mounted

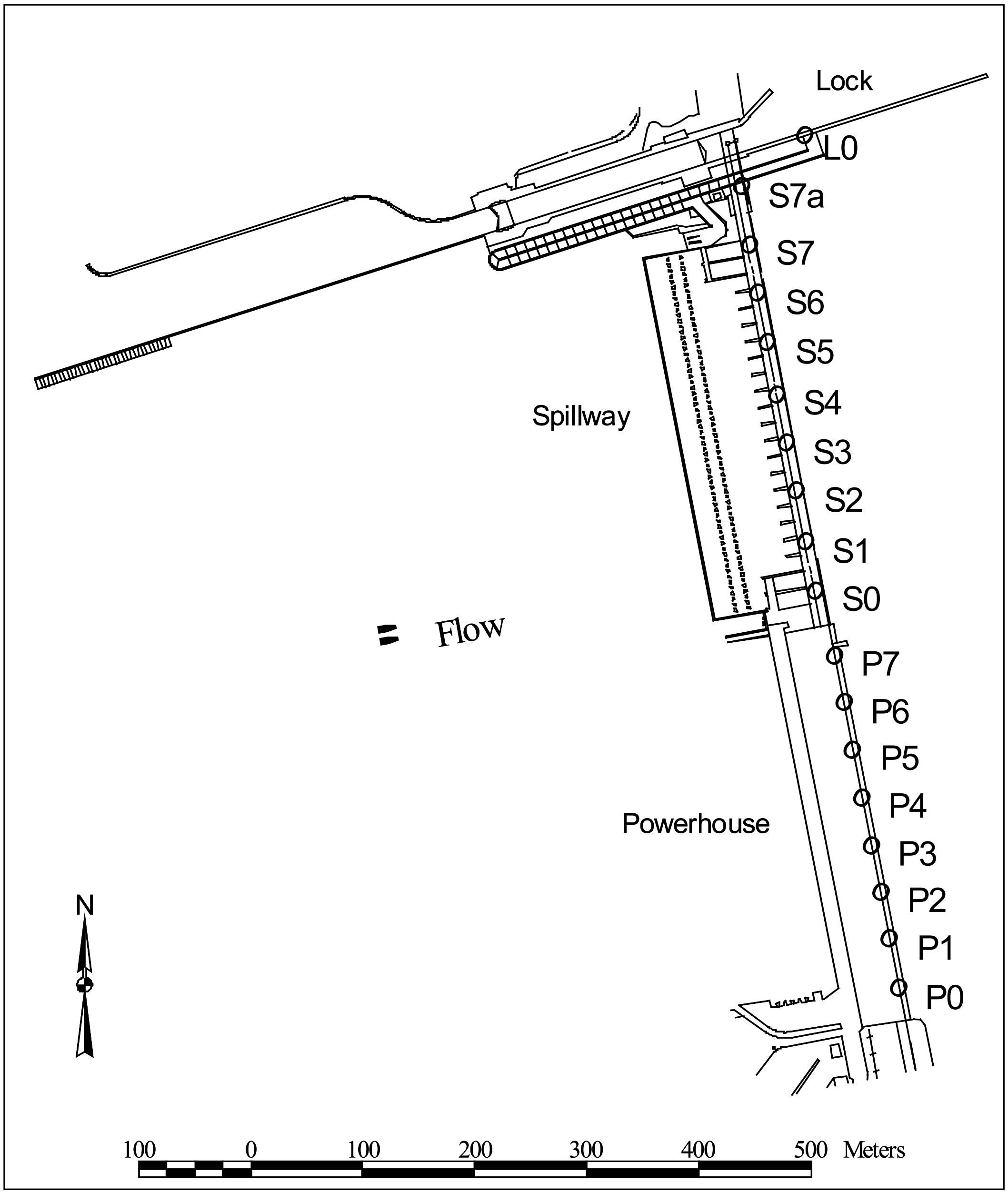

Figure 10. Map indicating locations and designations of antennas at the powerhouse, spillway, and lock of McNary Dam used during spring, 1999.

facing northwest toward the lock from the upstream exit of the Washington-side fish ladder and was tilted downward similar to those of the other banks. Installation of telemetry equipment was completed in a few days in mid-March.

The antennas within each bank were monitored as a group until a tag was detected. After initial detection on grouped antennas within a bank, the individual antennas of that bank were scanned sequentially from the northernmost to southernmost to determine the approximate location of the transmitter.

The sensitivities of the receiving systems were configured to provide maximum detection distance at each bank. The maximum sensitivity at each bank was limited by background noise. Background noise was greatest at the powerhouse, followed by the spillway and lock. Therefore, the receiver sensitivities were highest at L bank and lowest at P bank.

Tag frequencies and calibration information were entered into the receivers within 24 h of the release of tagged fish. The frequencies were monitored until the fish were detected, or up to 10 d (i.e., the estimated tag life) after release if they were not detected.

Data analysis

Data from each receiver were downloaded on a daily basis when tagged fish were in the reservoir. The data were imported to a relational database for proofing and preliminary analysis at the end of the field study period. Depth data from the tags were corrected for differences in temperature and elevation between calibration and working locations as described earlier in this report. Final analysis was done using the SAS System for Personal Computers (SAS Institute, Inc. 1989).

Results

The detection rate of tagged juvenile chinook salmon by telemetry equipment at McNary Dam was 83.3% (N = 25). Juvenile steelhead had a detection rate of 54.7% (N = 23). Seventy-two percent (18) of the chinook salmon detected were first detected (i.e., approached) at the spillway and 28% (7) approached at the powerhouse. The approach of steelhead to the dam was similar, 74% (17) approached the dam at the spillway and 26% (6) approached at the powerhouse (Figure 11). Approaches of both species to the spillway were predominantly near the north and south ends. A slight majority of chinook salmon were first detected near the south end of the spillway while most steelhead were first detected on the north end (Figure 11).

A slight majority of chinook salmon were last detected at the spillway, 56% (14) versus 44% (11) at the powerhouse. Chinook salmon were last detected at the powerhouse most frequently at the north end while last detections at the spillway were distributed more evenly (Figure 11). Fifty-two percent (12) of steelhead were last detected at the spillway, with 44% (10) at the powerhouse and 4% (1) at the lock. The final detections of steelhead at the powerhouse were split between the north and south ends while those last detected at the spillway were found mostly in the center (Figure 11).

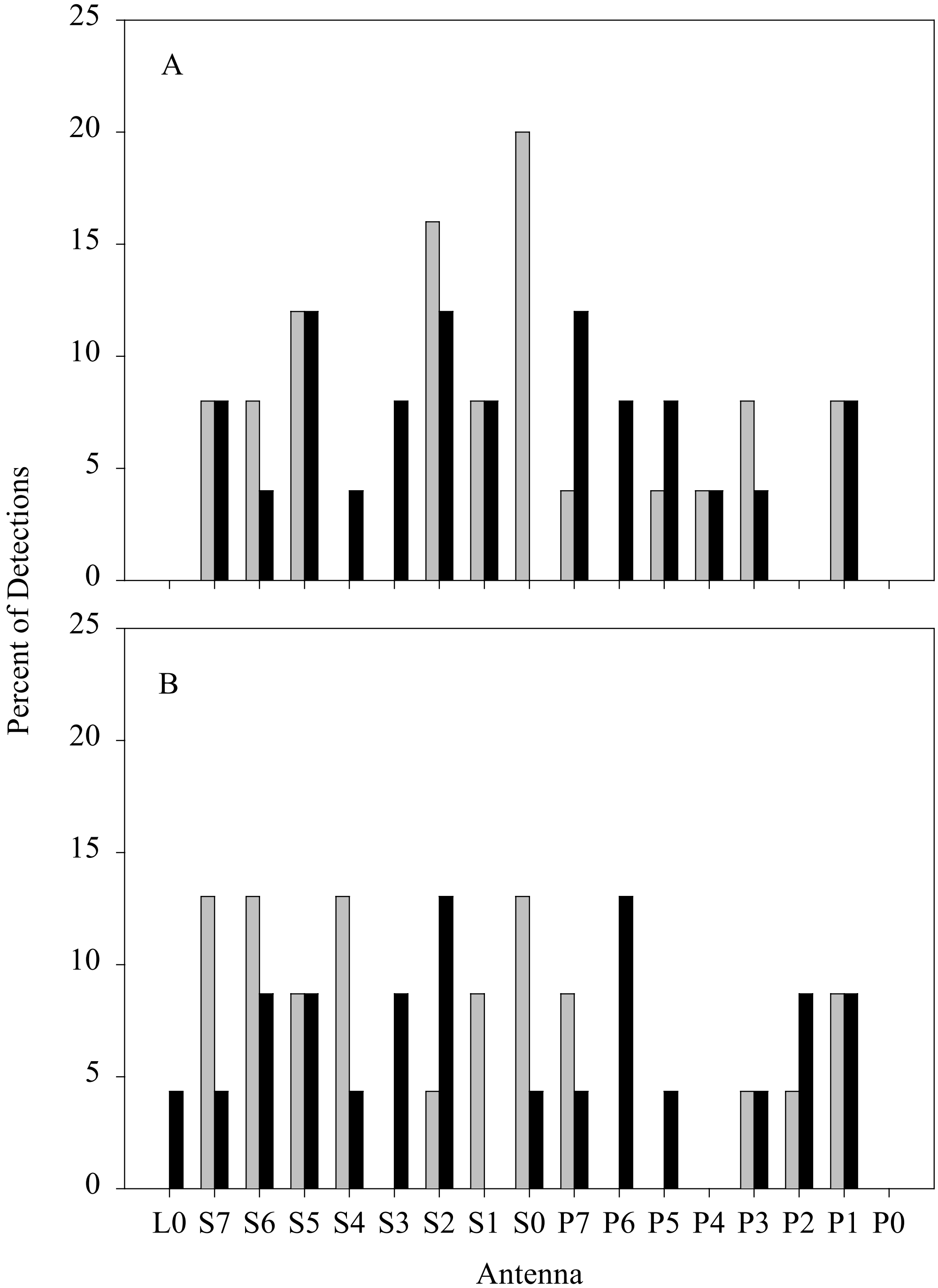

Figure 11. Percent of first (light bars) and last (dark bars) detections of juvenile chinook salmon (A) and steelhead (B) at antennas mounted on McNary Dam during spring, 1999. See figure 10 for antenna locations.

The median residence time of chinook salmon in the area of detection was 25.6 min (range 5.4 to 222.3 min). Steelhead residence times ranged from 4.7 to 988.5 min with a median of 30.9 min. The median depths during this time were 2.6 m (N = 482, range 0.2 to 13.8 m) for chinook salmon and 0.5 m (N = 1563, range 0.01 to 9.4 m) for steelhead. A second analysis was conducted after removal of influential data from 2 of the 23 steelhead detected. The large influence of these fish was due to the combination of long forebay residence times (430 and 775 min) and shallow median depths (0.01 and 0.47 m, respectively). Results of this analysis indicated a median depth of 1.3 m for the remaining steelhead.

Discussion

The results of this study indicate that median fish depths in the near-dam forebay were sufficient to compensate for ambient TDG levels of 125% for chinook salmon and 112.5% for steelhead. The depths of fish in the near-dam area were more than a meter shallower than those observed in Lower reservoir area. It is unclear why median depths were shallower in this area, but Beeman et al. (1999a) observed a similar change in 1997. Our results suggest that the current voluntary spill program limit of 120% TDG in tailraces and 115% in forebays can be expected to prevent the onset of GBT in juvenile chinook salmon and steelhead while they are in the near-dam forebay of McNary Dam.

Detection rates of radio-tagged fish were quite different between species. The equipment at McNary Dam detected 83% of the chinook salmon we released, but only 54% of the steelhead. Of the 19 steelhead that were not detected, four were located by mobile tracking in the Lower area. The fact that several fish were located in the area just upstream of the dam suggests that some may have reached the dam, but were undetected. Fourteen of the steelhead not detected at the dam were last located in either the Snake or Upper areas. These fish may have gone undetected at the dam for a number of reasons including loss to predators, reaching the dam and not being detected, reaching the dam after the tag battery had expired, and tag failure. It is interesting to note that although detection rates of steelhead were over 70% in 1997 and 1998, they were consistently lower, by almost 20%, than detections of chinook salmon (Beeman et al. 1999a, 1999b). Tag failure is an unlikely explanation for the difference between steelhead and chinook salmon detection rates. All fish were implanted with the same type of tag; we assume that the failure rate would be equal for both species. Predation, lack of detection and passing the dam after the tag battery had expired are all plausible sources of the differences in detection rates that could result from distinct migration behaviors in chinook salmon and steelhead.

Approaches to McNary Dam and residence times in the forebay from this study were more similar to those observed in 1998 than in 1997 (Beeman et al. 1999a, 1999b). Most fish approached the dam nearest the spillway and passed through in less than an hour. The similarities between 1998 and 1999 are most likely due to similarities in the river flow and proportion of the flow spilled between years. During the study period in 1998, an average of 48% of the river flow at McNary Dam was spilled compared to 43% in 1999 (data from U.S. Army Corps of Engineers). We also observed several differences between 1998 and 1999. Rather than approaching the dam mostly on the north end of the spillway as in 1998, detections in 1999 were split between the north and south ends. The median residence time of chinook salmon in the forebay was almost 50% longer than in 1998 while the residence time of steelhead changed little.

The location of the last detection, and presumed route of dam passage, was quite different in 1999 than in past years. Final detections for chinook salmon and steelhead were split almost evenly between the spillway and powerhouse while in 1997 and 1998 most fish were last detected at the spillway (Beeman et al. 1999a, 1999b). Although average flows in 1999 were most similar to 1998 levels, they were lower by an average of 1359 m^3/s (48 thousand cubic feet per second). Lower flows in combination with slightly reduced spill levels may have affected the route of fish passage through the dam.

The results of this study indicate that the median depths of both species in the near-dam, forebay despite being shallower than median depths observed in the Lower area, were sufficient to compensate for TDG levels of 125% for chinook salmon and 112.5% for steelhead. This suggest that the current voluntary spill program limit of 120% TDG in tailraces and 115% in forebays can be expected to prevent the onset of GBT in juvenile chinook salmon and most steelhead while residing in the near-dam forebay of McNary Dam. Our results also indicate that most of the radio-tagged juvenile chinook salmon and steelhead detected at McNary Dam approached the spillway and the majority resided in the forebay only briefly before passing the dam. The location of last detection, and presumed route of passage, was split almost evenly between the powerhouse and spillway for both species. Lower river flows and spill levels in 1999 may account for the differences from last detection locations observed in 1997 and 1998.

Acknowledgments

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